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Continuous gravity monitoring for CO2 geo-sequestration (2) a case study at the Farnsworth CO2-EOR field

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Abstract

We started continuous gravity monitoring using superconducting gravimeter at the Farnsworth CO2-EOR field. During the baseline measurements we detected the obvious decreasing trend, which is attributed to changes in the local water table. The CO2-EOR process will result in the redistribution of mass which may result in gravity signals, which is the principal signal of interest for this study. We must revise the observation plan to detect the subtle signals as precious as possible. With two SGs located in near sites making parallel SG and SG measurements can provide improved accuracy and sensitivity.

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Keywords: Farnsworth, superconducting gravimeter, monitoring, continuous measurements, CO2-EOR

1. Introduction

We have been developing a monitoring method for both lowering costs and increasing the safety in CO2 sequestration by complementing standard seismic survey with gravity monitoring. In many cases reservoirs are relatively thin and deep, resulting in subtle time-lapse gravity signals at the earth's surface. To cope with such situations, we need to improve the accuracy of surface measurements to detect the lateral migration of the CO2 plume. The superconducting gravimeter (SG) is distinguished from other gravimeters by superior precision, better than 1 nm/s2 (100 nGal) and by the ability to record gravity continuously over periods of months and longer. At the GHGT11 meeting we made a presentation regarding the model calculation of CO2 sequestration, which demonstrated that continuous gravity recording with superconducting gravimeters is a promising tool for practical monitoring (Sugihara et al [1]). Continuous microgravity recordings associated with conventional time-lapse measurements will probably improve the accuracy of the monitoring.

Originally we planned to perform this study at Gordon Creek Utah. The test site had to be moved to the Farnsworth site where CO2-EOR (enhanced oil recovery) is operated. In December 2012 we started baseline

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measurements with an iGrav SG at the test site in cooperation with the Southwest Regional Partnership (SWP) which was established by US Department of Energy.

2. Farnsworth Field

The Farnsworth field resides in the northwestern portion of the Anadarko Basin, a large structural basin containing significant oil and gas reserves. Oil production can be described as progressing through three phases as oil is removed from a reservoir. In the second phase, water, CO2 or other media is injected into the reservoir to drive the residual crude oil remaining after the primary oil recovery phase is completed. This method, that is EOR, allows additional oil in the reservoir to be extracted. The Farnsworth field is currently in the second phase of oil recovery. The average depth of the reservoirs at this filed is known to be about 7750 feet.

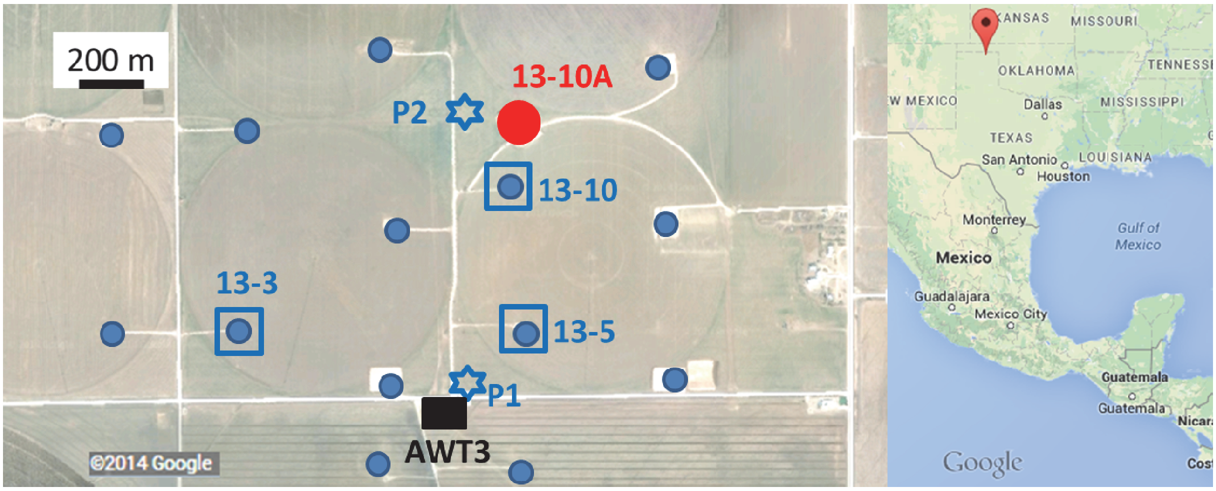

Fig. 1. The center part of the Farnsworth field, TX. AWT (Automatic Well Test Facility) pad is the place where iGrav SG is installed. A red solid circle 13-10A indicates the site where a new injection well was drilled. Small solid circles indicate well pads for oil production. Three rain gages are installed at the pads the name of which are indicated in blue rectangles (13-5, 13-10, 13-3). Blue stars (P1 and P2) indicate groundwater wells.

The water table at AWT3 pad lies at a depth of 600 feet below the surface. This ground water is pumped in close proximity to the measurement site and deposited on the surface in an agricultural sprinkling system. The sprinkling systems in this area consist of a moving boom 800/1600 feet long which rotates around a central pivot point. Water is pumped from a nearby well to the center of the boom and deposited through a ridged horizontal tube with hoses hanging down terminating in sprinkler heads. The booms rotate by motorized wheels which are programmed to cover the circular field over an approximately three day-cycle, however the exact watering pattern varies from field to field. The process described above will result in the redistribution of mass which may result in gravity signals at levels which are significant to this study.

Fig. 2. (Upper left): The optimum location for the observation hut was determined to be in the south east corner of the AWT-3 pad with the front door facing west. The concrete pillar is outside the hut for GPS measurements. The locations were chosen so that we could secure clear optical paths from a common point to both the GPS pier and the gravimeter piers, through the entry door of the hut. This could allow the pillar elevations to be precisely measured optically. (Upper right): The two concrete pillars for SG and AG measurements are inside the hut. The centers of the two pillars are separated by about 1 m. Three gravimeters, iGrav/10 SG, FG5/217 AG and CG5/352 portable gravimeter, were set from left to right. (Lower left) The well 13-6 is the active production well nearest to the monitoring site during the period December 2013 to June 2014, it is a reinjection well now. (Lower center) The ground water pumping station, which is used for agricultural irrigation, is located across the dirt road from AWT3. (Lower right) water is deposited through a ridged horizontal tube with hoses hanging down terminating in sprinkler heads. The booms rotate by motorized wheels which are programmed to cover the circular field over three day-cycle or shorter. It was monitored using rain gage.

3. Measurements

At first, three gravity observation pillars were constructed at the AWT3 pad. Two pillars were designed to protrude through the floor of the observation hut to be used as stable platforms for installing a SG and an absolute gravimeter (AG). A heavy duty pre-fabricated hut with dimensions of 8 feet wide x 12 feet long x 8 feet tall covers the two piers for gravity measurements (Figure 2a). A columnar pillar was constructed outside the hut for portable relative gravimeter and GPS. The hut was designed to accommodate an iGrav SG, and an AG (FG5 meter or A10 meter). The pillars were constructed from steel-reinforced concrete. The depth of the pillar was decided to be 1 m by two criteria: (1) Depth to extend below the frost line; (2) Depth to extend below any fill and at least 0.3 m into un-disturbed soil.

In December 2012 we started baseline measurements using an iGrav SG at the test site. The scale factor and drift rate of the SG were evaluated by co-located measurements with an absolute gravimeter (AG). Continuous recording using the iGrav SG had been paused due to budgetary constraints limit then resumed in November 2013. SGs have higher precision, lower noise and lower drift. The iGrav SG has an ultra-low drift of less than 0.5 microGal / month and a virtually constant scale factor. It will continue to provide an ultra-high precision continuous gravity reference for studying geophysical phenomena with periods from one second to decades. Usually after the first month, drifts are said to be extremely linear over many years, so annual or semi-annual AG measurements are sufficient for determining the linear drift rate.

Empirically, the drift rate of the continuous recording data is estimated using the TSoft program. After the resumption apparent drift rate of the iGrav10 (iGrav SG, serial number 10) was estimated to be much worse than the specifications AG measurements have been made every month. After confirming the drift by co-located analysis iGrav10 have been re-initialized. In March 2014 iGrav10 was removed and iGrav15 was installed for continuous measurements.

Strictly it is difficult to distinguish real gravity changes from time-varying instrumental drift. The best method is parallel SG and SG measurements located in close proximity. Repaired iGrav10 was installed in May 2014 for the parallel SG and SG measurements. The iGrav10, the drift of which had been evaluated to be still large, was removed and iGrav17 was installed in July 2014.

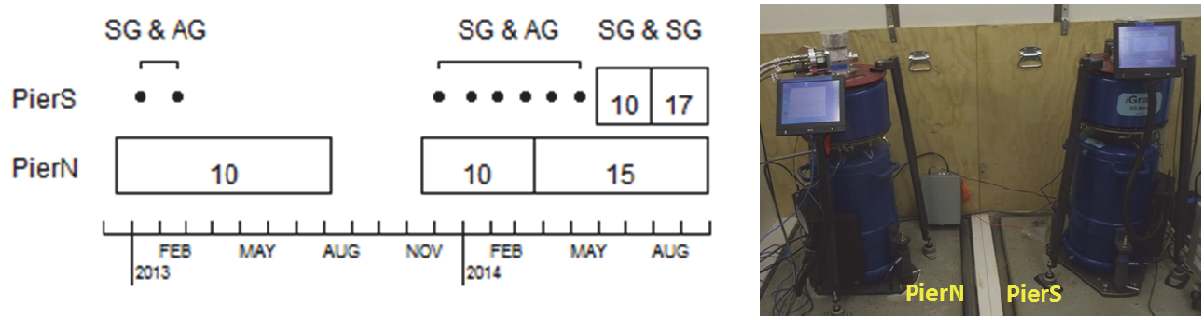

Fig. 3. (Left) Schedule of the two piers. Each solid circle indicates an absolute gravity measurements using FG5/217. Each rectangle indicates a continuous SG measurement. The number inside each rectangle is serial number of the iGrav SG. (Right) The iGrav15 SG, The iGrav17 SG from left to right.

4. Observed Data

We decomposed the 225-day continuous gravity data using the program BAYTAP-G into the trend components, tidal components and others (Figure 4 left). Generally the instrument operated well and performed within specified limits. The disturbances we encountered did not appear to affect the long period performance of the instrument which was the principal signal of interest for this study. If the change in gravity is real, on this scale, one might expect the most likely source to be changes in hydrology, specifically changes in the height of the water table. Several short-term events were observed in the trend components. The events correspond to storms accompanied by low pressure and/or heavy rainfalls (Sugihara et al., [2]).

Figure 4 (right) shows the unprocessed iGrav data which was recorded during the period 11/29/2013 to 3/10/2014. The drift of the iGrav10 have been larger than specifications. In an attempt to remedy the behavior the magnetic support field in the instrument was re-initialized several times during the period. This further improved the behavior however drift still remained. It should be noted that the trends appeared to be linear during each phase of the observation. Final results can be used with the linear trends removed with drift slopes calculated from linear regressions of each discrete observation period.

TSoft, which is developed by Royal Institute of Belgium, is a convenient program for the visualization and analysis of the iGrav15 data. Tidal analysis was performed with TSoft using tidal parameters obtained using the Eterna program (Fig 5). In the figure the gravity residual is expanded showing greater detail after the initial pump out period is completed. Here a total change of gravity on the order of 16microGal over the period of 4/20/2014 to 8/12/2014 (115 days) can be observed. This observation exemplifies the importance of parallel measurements with an absolute gravimeter and a second SG which has been well characterized. Without such corroboration, on this scale, it is impossible to discriminate secular changes from instrumental artifacts. Figure 5 (right) shows the observed data of the parallel SG and SG measurements during the period of 7/30 to 8/25. In the figure the difference between the two iGrav SGs is converging after the initial pump out period (Nawa et al., [3]). The periodic signal was due to the internal temperature of the hut exceeding the control set point of the iGrav SG electronics temperature controller (30 C). The high internal temperatures were in part due to the extreme ambient temperatures during this period which reached 45 C. Except the periodic noise SG data observed at AWT3 has as good quality as at geodetic observatory. The periodic noise will be fixed by revising accommodation of the observation hut.

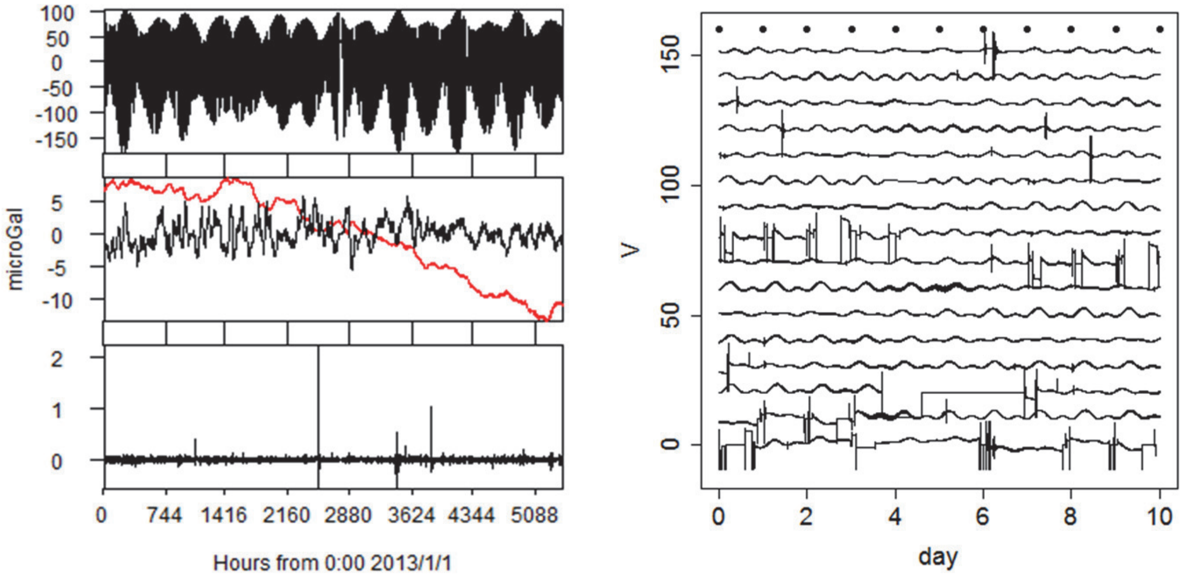

Fig. 4.(Left): Decomposition of the 225-day continuous gravity data using the program BAYTAP-G into tidal effects (upper panel), trend component (red line in middle panel), response to air pressure (black line in middle panel) and irregularities (lower panel). (Right): The unprocessed iGrav data which was recorded during the period 11/29/2013 to 3/10/2014.

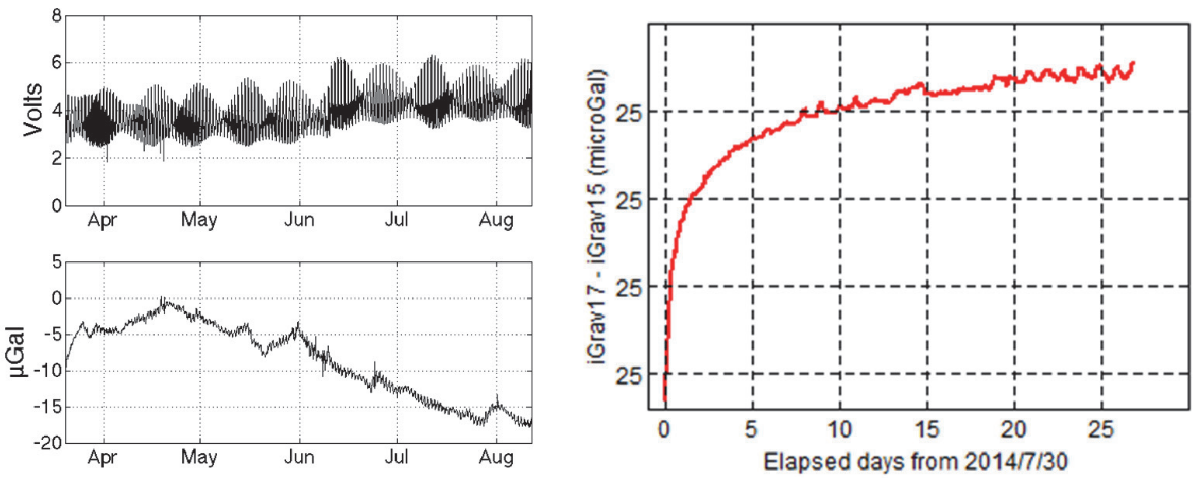

Fig. 5. (Left): The iGrav15 data during the period of 4/20/2014 to 8/12/2014. (Right): The observed data of the parallel SG and SG measurements during the period of 7/30 to 8/25.

5. Discussion

The CO2-EOR process will result in the redistribution of mass which may result in gravity signals, which is the principal signal of interest for this study. We observed the obvious decreasing trend in the iGrav data (Fig 4 left, Fig 5 left). The trend can be attributed to changes in the local water table because of the good correlation with activity of the sprinkler system. The effects of the sprinkler system can be summarized as follows: (1) Water pumping may result in changes in the local water table level resulting in subsurface mass changes at an approximate depth of 650 feet. (2) Surface sprinkling will result in changes in soil moisture resulting in a mass change at the surface. Referring Figure 6 (left) the second effect is much smaller than the first effect. There are several tanks at the AWT3 base. The effect of redistribution of mass in the tanks is negligible. Soil moisture around the observation hut, however, results in observable gravity signals. The principal signal of interest regarding CO2-EOR process can be detected after evaluating the other observable gravity signals.

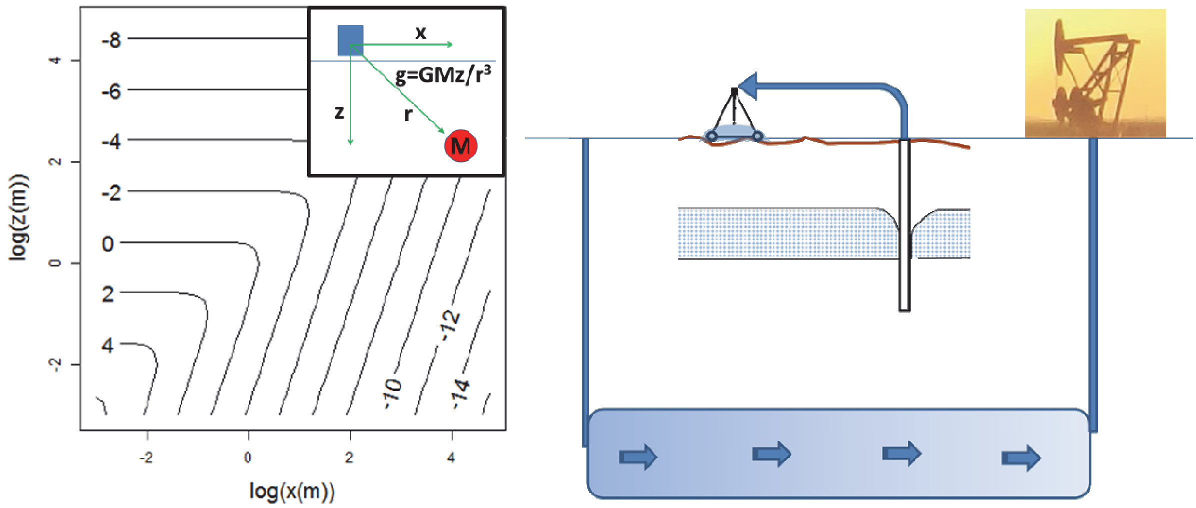

Fig. 6. (Left): How large gravity (in microGal) is added to the gravimeter by a unit mass that is located at the point (x, z). (Right): Schematic diagram of the CO2-EOR process and the sprinkler system, which will result in the redistribution of mass which may result in gravity signals.

6. Conclusions

Originally we planned to perform this study at Gordon Creek Utah. The test site had to be moved to the Farnsworth site where CO2-EOR is operated. Roughly it is more difficult to detect gravity changes accompanying CO2 sequestration at the Farnsworth than at Gordon Creek because (1) smaller injection rate and (2) EOR effect. We must revise the observation plan to detect more subtle signals. With two SGs located in near sites making parallel SG and SG measurements can provide improved accuracy and sensitivity. By varying the position of the two SGs, the measurement can be focused at a specific depth (Kennedy et al., [4]). We are planning such measurements at the Farnsworth site in 2014.

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